The Changing Face of Structural Design for Fire

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Introduction

Disasters, whether natural or manmade, are a test to design practices and in many cases prove the vulnerability of our infrastructure. Disasters force us to revisit our perception of the safety inherent to the environment in which we carry out our everyday activities. Therefore, associated to disasters there is always anxiety and pressure to revisit those practices that lead to unsatisfactory performance. The behaviour of structures in a fire has faced, in the events of September 11th 2001, one of those disasters that have directly challenged our current design practices. *Anxiety has spread over those individuals linked to infrastructure that can be considered as potential targets for terrorist activity.* As we understand more about what happened with the World Trade Centre Buildings questions are being raised about our current design practices, proposed amendments and the tools that we use to evaluate the performance of structures in the event of a fire. Furthermore, the collapse of the World Trade Center buildings 1, 2 and 7 occurred within a period where design practices were being pushed out of an environment of prescriptive requirements to one where structures will instead be evaluated on the basis of their performance as predicted by engineering tools.

To analyse the response of the designers to this disaster it is necessary to pose a series of questions. The first question relates to the actual nature of the disaster that is provoking the reaction. *Why did these buildings collapse, carrying the lives of so many people?* The answer to this question will be the product of a forensic investigation [1] that we do not intend to discuss it any further here. Nevertheless, from this investigation will result different conclusions, some pertaining to the nature of the event, some pertaining to the nature of the buildings themselves and some pertaining to the design and construction practices involved in the development of these buildings. The latter point is the one of greatest interest to the public since it is associated to the safety of current and future buildings designed under the same principles. The general question then becomes: in which way is fire incorporated into the design of structures? This question is then followed by a series of interrogations that relate to the details of the design practice, which are of a more fundamental nature but still directly concern the safety of our built environments.

Deepening into the detailed processes, a fire affects a structure through the heat it supplies to all the constructive elements. Thus the first pillar of a design process is the understanding of the fire, the growth process it undergoes and the heat it supplies to the structural elements. As much as it is clear to everyone that a fire affects a structure, it is not as common to understand how a structure can have an impact on the growth of a fire. Nevertheless, it is the case that as the structure heats-up energy will be provided by the structural elements to the fuels and so enhance the rates of fire growth. Furthermore, deformation and failure of different structural components will affect the air supply to the fire and consequently the heat released. As a result structural and fire behaviour are coupled.

Once the relationship between the fire and the structural elements has been defined it is important to understand how the structural materials will react to that external heat input. Material properties will change and it is accepted that all parameters describing the material strength will deteriorate, but this is only one part of the process. The geometrical features of structures are also affected by fire since materials expand with temperature and the constraints inherent to the geometry of the structure result in significant generation and redistribution of stresses. This key point is probably the most significant impact on structures in fire, and is rarely considered in the design process.

Once these fundamental questions have been addressed it is important to establish sources of uncertainty. Uncertainty or "error" can range from the purely probabilistic nature of the fire event to deterministic estimation of the variability of the thermal properties of insulation materials used for fireproofing. The combination of analysis on the basis of fundamental physical principles, simplifying assumptions and error estimates, represent the design tools.

Structural Fire Engineering tools

The design tools used by Structural Fire Engineers (SFE) address the two different aspects explained in the previous paragraph (material degradation, geometric effects from expansion). It will be the SFE's hope that all these tools are based on sound and fundamental engineering principles and that the answers obtained are exact thus include no potential for "error" or variability. The reality is that fire and structures are very complex problems whose complexity increases exponentially when coupled. No tool can solve the integrity of the structures in fire problem absolutely, thus all tools rely on a number of simplifying assumptions. Many of these assumptions have been thoroughly studied, their error bars established and their results validated. Therefore, it has been the belief of the SFE that the tools provide accurate and robust results and on this basis has been made part of the design process.

The progression towards performance, rather than prescriptive design, and the precedent set by the collapse of the World Trade Center buildings require from the structural fire engineer a revisit of the design procedures and the tools, with the objective being to improve , modify and gain further confidence. The following paragraphs will schematise design practices commonly used to present those areas that are being revisited through fundamental research.

Table 1 provides an attempt to schematise some of the design methods commonly used to analyse the performance of structures in the event of a fire. The design framework defines a sequence of events. The architects provide a design from which the structural engineers will develop a structural analysis that will take into account all requirements that will guarantee that the building will support its own weight and perform adequately to its intended use. The architectural design and structural analysis do not include at this stage the potential for a fire. Any considerations for fire introduced by architects at this point are mostly associated with prescriptive requirements but include no evaluation of the impact that these measures can have on the structure's performance. Once the structure has been designed the fire is then incorporated. This is the common approach. This can be done either through prescriptive requirements that are fundamentally based on the use of the building or through an engineered analysis of structural performance.

The former provides no indication of the behaviour of the structure in the event of a real fire and thus is unsuitable for any event that will escape the range covered by the historical data that support prescriptive design.

An important aspect of the latter methodology is to establish a design fire. The choice of design fires can be achieved in a number of different ways. It could include a series of most probable events, "worst case scenarios" or could lead to the definition of protection systems and maintenance protocols that will constrain the fires to an acceptable level. The main limitation of the "Design Fires" is that any event (i.e. terrorist attack, arson) that escapes the chosen range of fires could lead to an unacceptable performance. However the reverse is also true and by addressing specific design fires, events beyond that addressed by Building Codes, can be considered and/or quantified. The outcome variables such as structural behaviour, life safety, property damage are all coupled. In some cases a function that minimizes all negative outcomes is not possible. The next step is therefore a probabilistic approach. Probability based decisions can be limited by the lack of a comprehensive set of statistics. Fires are, by definition, rare events. Given a building, its usage, its life and the potential threats, it is for some cases difficult to establish a probability database that gives adequate confidence. This is therefore a topic for further research.

Design Step	Tools	Assumptions	Limitations
Architectural Design			
Structural Design	Analytical design methodologies Experimental Values Finite Element Numerical Simulations	Structural design is conducted without the inclusion of a fire	The global evolution of the structure with the fire is not included as part of the evaluation of the design alternatives The uncertainty in the properties necessary for the calculations increases because high temperature data is limited for some materials and not-well-understood phenomena such as “spalling” still needs to be included.
Design Fires	Historical evaluation of occurrence probabilities Analytical tools to quantify fire growth Numerical Simulations of Fire Growth (Zone Models, CFD Models) Empirical/Analytical/Numerical methods to analyse heat input to structures Fire Protection Methods (i.e. sprinklers, fuel control, venting) to define fire scenarios	The structure is designed to accommodate a fire that has a high probability of occurrence. The definition of the fire is given on the basis of an assumed performance or lack thereof, of a multiplicity of elements (i.e. smoke evacuation, sprinklers), typical or known fuel load density, compartment dimensions etc	Ignores events that exceed the pre-defined scenarios.
Fire Resistance	Standard testing of individual components to assess fire resistance (Fire Rating) Parametric Curves for more realistic scenarios	The fire can be defined by a standard Temperature vs. Time curve, as per the test furnace (ISO-834 [2]). If the standard fire is deemed not to represent the “Design Fire” an equivalent Rating can be extracted from a different Temperature vs. Time curve (parametric curves) The feedback from the structure to the fire can be ignored. Failure is defined by attainment of a critical temperature of an individual structural element; or rate of deflection of specific elements.	Does not address the fundamental heat transfer mechanisms controlling heat exchange between a fire and a structure Ignores the impact that geometrical effects have on structural behaviour (i.e. restraint thermal expansion) Definition of failure in real structural response to fire, yet to be quantified or defined.
Fire Protection	Fire Proofing to achieve required Fire Ratings	Properties of insulating material are well characterised. An extrapolation from furnace test behaviour to a real fire can be expected. Protected steel structures do not deform in fire. Concrete structures do not spall in fire. Application, maintenance and life time have no bearing on the performance of fire proofing materials.	There is not enough data available to support the assumptions on fire proofing material properties. Protected steel structures also deform in real fires as even with fire proofing structural elements can reach temperatures of approx 500C.. Concrete structures spall in fire unless specific detailing provided to limit this event. Properties of insulating material are not well characterised and/or not available in the public domain. Furnace data can only be extrapolated to a fire for a very limited set of conditions.

Table 1 Commonly used design methods, common assumptions and known limitations

Given the "Design Fires" a series of sophisticated tools can be used to establish the growth of the fire and its impact on the structure. The main constraint of these tools is associated with the interface between the fire and the structure. Most models are computationally intensive therefore solutions are obtained for the fire without accounting for the structure and the impact that its heating can have on the fire. Furthermore, close to the interface (fire and structural material surfaces) there is significant uncertainty associated with the performance of these tools.

The coupling of the structure and the fire is therefore done in a somewhat artificial manner. The classical approach is to physically test each individual element against a standard fire curve and obtain a rating based on when the structural element reaches a pre-defined critical temperature. This is then called the fire resistance time. This form of test could be substituted by calculations instead. These can use as input the standard fire (ISO-834 [2]), "parametric curves" [3], or the output of the calculations performed with design fires. It has long been recognized that real fires are affected by multiple factors, thus a single "standard fire" does not suffice.

The last stage of the design process is to introduce fire proofing to obtain the desired rating, by limiting heating of the structural elements, over time. Numerous methods exist to establish the required insulation [5] but they all imply a component of empirical data and uncertainty. As indicated in Table 1, this component of the design process has strong limitations and represents a very active area of research. These limitations and the proposed solutions will be discussed in the final section of this paper.

The above description clearly establishes areas where improvements can be made to this structural fire engineering approach and these improvements represent the new face of structural design for fire. There is a strong evolution towards an integrated design process that incorporates fire behaviour into the architectural and structural design processes from concept stage. The benefits of this approach are significant because it allows optimisation of the structural design to meet the architectural, structural and fire safety needs. To achieve this integration it is necessary to address areas where the tools are not coupled i.e. the interface between the structure and the fire. Numerical models used to predict structural behaviour and methods to quantify fire growth are therefore being coupled to encompass the dynamic interactions between the fires and the structures [6].

Optimisation of fire growth models has become necessary given the constant evolution of the architectural features of buildings. Figure 1 shows a traditional construction that given its geometry will require 120 minutes of fire resistance. This post World War II building will be of similar construction to those used for the tests that lead to the current ISO-834 standard fire. In a modern building (Figure 2) that includes much larger areas of glazing the intensity of the fire will be different. Thus the same rating will not apply. For this particular example, modelling demonstrated that the glazing resulted in a reduction in temperature that allowed a rating of 60 minutes rather than the assumed 120 minutes.

The Broadgate Phase 8 fire in London, UK and the subsequent Cardington frame fire tests have allowed researchers to fully investigated and understand the behaviour of whole frame composite steel-concrete structures in response to fire [7,8,9]. In June 1990 a fire developed on the first floor of the 14-storey Broadgate building. The total duration of the fire was in excess of four-and-a-half hours, with a severe period for about two hours. Flames temperatures in excess of 1000°C were noted. The structure of the building consisted of composite steel deck/concrete floors. The steel structure was partially unprotected at this stage of the construction. Despite some large deflections (see Figure 3), there was no collapse of any of the columns, beams, or floors. The Broadgate fire prompted a large-scale test program on an 8 storey composite steel frame at their test facility in Cardington, UK. The Cardington Frame fire tests provided a wealth of experimental evidence about how whole frame composite steel-concrete structures behave in fire. The main conclusions were that composite framed structures possess reserves of strength by adopting large displacement configurations with catenary action in beams and tensile membrane behaviour in the slab [8,9] Furthermore, for most of the fire duration, thermal expansion and thermal bowing of the structural elements rather than material degradation or gravity loading govern the response to fire. Large deflections were not a sign of instability and local buckling of beams helped thermal strains to move directly into deflections rather than cause high stress states in the structure. Only near failure, gravity loads and strength will again become critical factors.

State of the art approach

These findings and the additional motivation provided by the WTC collapses have resulted in a drastic shift of the design process, away from single structural element principles as forms part of the Standard Test approach, and towards a global structural analysis based on design fires. Broadgate and WTC show two different potential outcomes that can only be predicted via a detailed global analysis of the structural behaviour through the fire event.

The need to use “Design Fires” still remains an unresolved problem. The volume of the calculations required to address the different aspects of a fire implies that only a reduced number of scenarios can be fully studied, thus educated engineering solutions are still necessary. Important strides are currently being made to optimise the necessary tools to allow for a more systematic evaluation of a multiplicity of scenarios where the “Design Fires” can be substituted by concepts such as design to obtain a “Minimum Damage Potential.”

Structural Fire Engineers have in their hands a large number of reliable and sophisticated design tools. These tools can still be improved but currently are appropriate for design purposes. Modern structural design for fire is making more and more use of these tools. The advantage of this approach is that it introduces more physical analysis to the design process and allows a more adequate quantification of performance and uncertainty. The evolution of design, and of the tools used in the process, is geared towards an increase in integration and efficiency and a constant reduction in uncertainty and error.

To end, these tools require detailed understanding of the principles underpinning them, thus proper training is essential, not only for the designers but also for those professionals interacting with Structural Fire Engineers and those involved in the approval and inspection process.

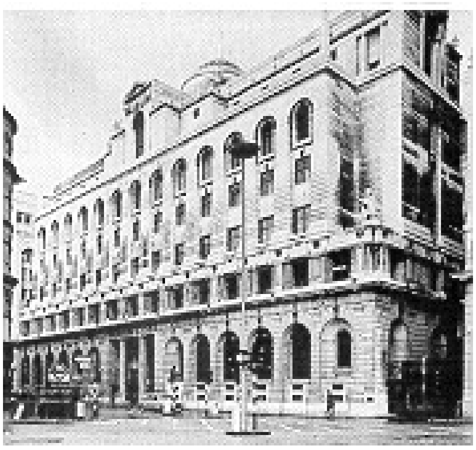

Figure 1 Traditional Office Building

Figure 2 Modern Office Building, Greater London Authority Building (GLA)

Figure 3 Aftermath of the Broadgate Fire

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